APPLICATION NOTE

SAR Probe Calibration and System Verification Considerations for Measurements at 150 MHz – 3 GHz

January 2007
(Revised)

Laboratory Division

Office of Engineering and Technology

Federal Communications Commission

Introduction

The SAR measurement procedures in IEEE 1528-2003 and Supplement C 01-01 were established primarily for testing wireless handsets in the 800 MHz and 1800 – 1900 MHz bands. Although tissue dielectric parameters are also defined at a few other selected frequencies, as new products and services are introduced in other spectrums such as Parts 25, 27, 90 and 95, these previously established measurement procedures could become unclear and insufficient. Because tissue dielectric properties are frequency dependent; the tolerance limits defined by measurement protocols have led to implied frequency intervals within which the dielectric parameters are valid. During measurements these frequency intervals can often be reduced by the frequency characteristics of actual tissue media (recipe) and frequency response of SAR probes in the media. In certain situations, it would be desirable to determine if additional probe calibrations are necessary for measurements in neighboring frequency bands.

Reference dipoles used for system verification are also influenced by the effective frequency interval imposed by probe calibration and tissue media requirements. The dipoles are only defined at selected fixed frequencies by measurement protocols. As both broadband and narrowband services are introduced at various frequencies and adjacent spectrums, tuned dipoles could be unavailable at the required probe calibration, tissue media and test device frequencies. Therefore, it would also be beneficial to know if dipoles intended for nearby frequencies may be used to verify measurement accuracy. This application note provides guidance and discussions on probe calibration, system verification and tissue dielectric parameter requirements for circumstances where existing protocols are insufficient. When necessary, the procedures may be revised as new information becomes available through standards organizations and other reliable sources.

Tissue Dielectric Properties

Measurement protocols require the dielectric constant (ε_r) and conductivity (σ) of tissue media to be within ±5% of the defined target values. In addition, dielectric measurement tolerances < ±5% are also required. Since drifts in tissue media properties and errors in dielectric measurements can both cause SAR discrepancies, tissue dielectric target and measurement tolerances are handled separately by different uncertainty components. The dielectric parameters are valid within frequency intervals determined by the frequency characteristics and defined tolerance limits for ε_r and σ. SAR differences due to small changes in tissue dielectric parameters may be analyzed qualitatively according to the SAR sensitivity data reported by IEEE SCC-34 and similar information confirmed by SAR system manufacturers.[1] The results are based on near-field dipole exposure conditions, which may not fully represent actual device test conditions or facilitate quantitative extrapolations. However, it can be estimated that target tolerances of +5% in ε_r and -5% in σ could introduce peak and 1-g SAR underestimations of 8.4% and 5.8% (See Attachment 1). With similar tolerances in dielectric measurements, underestimations of 16.8% and 11.6% are possible. Differences in tissue media frequency

[1] See definition of SAR sensitivity in IEEE Standard 1528-2003. SAR sensitivity was analyzed by IEEE SCC-34 during the development of P1528, according to near-field conditions of dipoles. The results at specific frequencies were not included in the final standard.

characteristics between probe calibration and routine measurements can introduce additional variations; especially for measurements further away from the probe calibration frequency.

Tissue dielectric parameter tolerances and dielectric measurement uncertainties can reduce measurement accuracy. Frequency implications for tolerances in head and body target dielectric parameters are illustrated in Attachment 1. The plots indicate that values of ε_r and σ at a specific frequency can only satisfy dielectric tolerance requirements in a limited frequency range.[2] Measurements below 300 MHz are generally limited to ±50 MHz or less. At above 350 MHz, measurements are mostly limited to ±100 MHz to maintain 5% tolerance in σ, with the exception for 835 – 915 MHz because of the way target values are defined.[3] The upper and lower frequency intervals for ±5% tolerances in head and body ε_r are mostly asymmetrical. The changes in ε_r are much steeper below 800 MHz. Below 300 MHz, the frequency range corresponding to -5% tolerances in ε_r is approximately 50 MHz. This implies measurements > 50 MHz below the probe calibration or device mid-band frequencies may not satisfy measurement protocol requirements. The similar analysis for 5% tolerances in σ also indicates a frequency interval of approximately 50 MHz at below 300 MHz. As frequency increases, the intervals gradually expand to about ±100 MHz at 3 GHz.[4]

The frequency constraints of several tissue recipes similar to those recommended by IEEE 1528 are illustrated in Attachments 2 and 3. The measured ε_r and σ for head tissue media are identified by solid lines and the required target values are shown in dash lines. The corresponding parameters for ±5% and ±10% tolerances are indicated by dotted lines. The plots illustrate that the effective frequency intervals for these common tissue recipes are typically smaller than those allowed by dielectric tolerance limits defined in measurement protocols. The reduced frequency interval is mostly related to differences in frequency characteristics between the defined and measured dielectric parameters.[5]

Attachment1:Tissue Parameter Variations | Attachment 2: 5% Tolerances | Attachment 3: 10% Tolerances

The effective frequency interval of a probe calibration can be influenced by deviations in ε_r and σ and differences in tissues recipes between probe calibration and routine measurements. The frequency characteristics of an individual SAR probe and its response to specific tissue media may trigger additional limitations. Hence, the dielectric properties of tissue media used in SAR

---

[2] Target dielectric parameters are frequency dependent. The frequency range for specific values of ε_r and σ to remain within ±5% tolerance can be determined by drawing a horizontal line across the curves in Attachment 1. The range of values for ε_r and σ to remain within tolerance at a specific frequency is identified by drawing a vertical line across the curves on the plots. Valid dielectric parameters should be within the region delineated by the ±5% tolerance curves within a desired frequency interval.

[3] Frequency intervals are narrower in 835 – 915 MHz.

[4] Irregular steps in target values for σ at 1800-2000 MHz and below 900 MHz also result in irregular frequency intervals.

[5] A few proprietary broadband tissue recipes are available, which may provide better matched dielectric parameters across a wider frequency range. However, more investigations are needed to determine the exact characteristics of these broadband tissue media.

measurements should satisfy the dielectric parameter requirements imposed by both probe calibration and routine measurements.

SAR Probe Calibration

SAR probe calibration concerns are examined for measurements at 150 MHz – 3 GHz. SAR variations due to tissue dielectric parameter tolerances and SAR sensitivities are also reviewed for both probe calibration and routine measurements. Other factors such as field polarization and direction of incidence, probe isotropy introduced by local field gradients, probe boundary effects error, signal modulation and device output power levels that may affect probe calibration and routine SAR measurements also need considerations. The validity of a probe calibration point with respect to measurement frequencies, tissue dielectric properties and other measurement parameters of the SAR system should be confirmed for all measurements according to protocols.[6]

Probes should be calibrated either by the manufacturer or an accredited calibration facility according to procedures described in IEEE 1528. The tissue dielectric tolerances and probe calibration methods required by protocols typically enable probes to be calibrated with an effective frequency range of at least ±50 MHz; sometimes up to ±100 MHz. However; the useful frequency interval can often be reduced due to differences in tissue dielectric properties between probe calibration and routine measurements. Therefore, besides analyzing the frequency implications of tissue dielectric parameters, the frequency responses of SAR probes and individual tissue recipes should also be considered to determine the ultimate frequency range of a probe calibration required by the intended measurements.

The following procedures are recommended for measurements at 150 MHz – 3 GHz to minimize probe calibration and tissue dielectric parameter discrepancies. In general, SAR measurements below 300 MHz should be within ±50 MHz of the probe calibration frequency. At 300 MHz to 3 GHz, measurements should be within ±100 MHz of the probe calibration frequency. Measurements exceeding 50% of these intervals, ±25 MHz < 300 MHz and ±50 MHz ≥ 300 MHz, should follow these *additional steps*.[7] (1) When the actual tissue dielectric parameters used for probe calibration are available, the differences for ε_r and σ between probe calibration and routine measurements should each be ≤ 5% while also satisfying the required ±5 % tolerances in target dielectric parameters. (2) When nominal tissue dielectric parameters are specified in the probe calibration data, the tissue dielectric parameters measured for routine measurements should be less than the target ε_r and higher than the target σ values to minimize SAR underestimations. Otherwise, a thorough analysis of the effective frequency interval supported by the probe calibration and dielectric medium should be included in the SAR report to substantiate the test results.[8] Alternatively, the measured 1-g SAR may be compensated with respect to +5% tolerances in ε_r and -5% tolerances in σ, computed according to valid SAR sensitivity data, to reduce SAR underestimation and maintain conservativeness.[9]

[6] Measurements should be in accordance with Supplement C 01-01, IEEE Standard 1528-2003, SAR system manufacturer specifications and other FCC recommended procedures

[7] These steps are typically not required when probe calibration and device test frequency intervals are properly matched; for example, testing of handsets in the Cellular and PCS bands.

[8] Plots similar to those in the Attachments may be used as part of the analysis and substantiation.

[9] The SAR sensitivity data in Attachment 1 and those confirmed by system manufacturers may be used.

When thorough analysis is required for the ***additional steps***, the following should also be considered. The probe conversion factor and its frequency response, with respect to the tissue dielectric media used during probe calibration and routine measurements, should be examined to determine if the effective frequency interval is adequate for the intended measurements to satisfy protocol requirements. Measurements within the required frequency interval should satisfy an expanded probe calibration uncertainty (k=2) ≤ 15% for all measurement conditions. When SAR is reported within 10% of the SAR limit, differences in field conditions and effects of output power levels on signal modulation between probe calibration and routine measurements should be examined to determine probe calibration validity.[10] Probe isotropy should also be assessed by rotating the probe in 15º increments at the peak SAR location of the zoom scan and accounted for in the measurement uncertainty. These other items can contribute to additional SAR differences, especially when the probe calibration, tissue dielectric parameters and device test frequencies are misaligned.

SAR System Verification

SAR system measurement accuracies are verified with reference dipoles defined in IEEE 1528. Additional dipoles vigorously validated by manufacturers with both numerical and experimental procedures similar to those used by IEEE 1528 are also available at a few other frequencies. The dipoles implemented by manufacturers may vary in construction and there are usually slight variations in dimensions from those defined in IEEE 1528. This may introduce differences in SAR target values where the calibrated SAR of such dipoles may deviate from those defined in IEEE 1528; for example, by 5% or more. Other factors, such as phantom shell thickness, tissue dielectric parameter tolerances and SAR sensitivity can also affect both the calibrated and routinely measured dipole SAR values. For products in new spectrums, reference dipoles may not be available within the frequency interval of a probe calibration or device transmission band. Under such circumstances, using existing dipoles intended for the nearest adjacent frequency bands may be the only alternative to examine measurement accuracy.[11]

Reference dipoles specified in IEEE 1528 and those available from SAR system manufacturers are used to verify SAR system measurement accuracy at 300 MHz – 3 GHz. The 1-g or 10-g SAR values measured using the required tissue dielectric parameters should be within 10% of the manufacturer calibrated dipole SAR values.[12] The extrapolated peak SAR value at the phantom surface above the dipole feed-point should generally be within 15% of the required values.

---

[10] The SAR of noise-like digital modulations can be affected by the signal voltage crest factor and peak-to-average power ratios, which may not be compensated easily according to current probe calibration and measurement methods.

[11] When reference dipoles are unavailable, system verification may not be feasible. Therefore, at least for the interim, the alternative procedures described in this document may be the only means to verify system specifications and routine measurement accuracy.

[12] These manufacturer calibrated dipole target SAR values should be substantially similar to those defined in IEEE Standard 1528. The SAR discrepancies should be mainly due to minor variations in physical dimensions and variations in small elements used for tuning to maximize RF coupling. Vigorous validations are required when the calibrated target SAR value of a reference dipole is substantially different; for example, more than 10%, from those defined in IEEE 1528. Some justifications may be necessary for SAR targets greater than ±5% of the defined values; for example, according to the long-term history of SAR measured previously for that individual dipole.

When other radiating sources instead of reference dipoles are used for system verification, vigorous validations are required to determine SAR target values. SAR measurements with system verifications using non-standard RF sources should be submitted to the FCC for equipment approval.

The purpose of SAR system verification is to confirm measurement accuracy according to the tissue dielectric medium, probe calibration and other system operating parameters used to measure the SAR of a test device. For most systems, probe calibration frequencies typically coincide with reference dipole frequencies. To satisfy probe calibration and tissue dielectric parameter tolerance requirements, SAR measurements are typically limited to approximately ±100 MHz of the probe calibration frequency; ±50 MHz when below 300 MHz. Similarly, the SAR target values of reference dipoles are also calibrated in accordance with these implied probe calibration and tissue dielectric parameter conditions. When products are introduced at new frequencies, reference dipoles may not be available within the probe calibration or test device frequency range.[13] Sometimes the reference dipole, test device and probe calibration frequencies could be substantially misaligned where measurement accuracy may not be confirmed easily.

At above 1.5 – 2 GHz, reference dipoles can typically maintain return losses of -15 dB or better for approximately 150 – 200 MHz; therefore, additional calibrations at offset frequencies may provide the necessary SAR target values for system verification at nearby frequencies using the same dipole.[14] For purpose of this document, this is referred to as alternative system verification method A. The measured SAR should be within 15% of the manufacturer calibrated target at the offset frequency. The SAR, on a long term basis including all previous measurements, should have a coefficient of variation < 3%; that is, (standard deviation)/mean < 0.03. At lower frequencies and also depending on the frequency, return losses of -15 dB or better are typically limited to 15 – 100 MHz for these reference dipoles; therefore, it is not always feasible or practical to use the dipole outside its resonance frequency range. However, the impact can be much less if the dipole is measured at its resonance frequency using tissue media intended for nearby frequencies. As illustrated in Attachments 3, changes in tissue dielectric parameters within a frequency range of ±100 – 250 MHz are usually within ±10%. Therefore, it would be practical to establish a new SAR target at the dipole frequency according to probe calibration and tissue dielectric medium used by the test device at nearby frequencies to confirm system measurement accuracy. The SAR target obtained in this manner may be valid only for the particular measurement configuration using that dipole with the specific probe calibration, tissue medium and specific phantom. This is referred to as alternative system verification method B. It requires vigorous substantiation and is only intended for interim use when a required reference dipole, as defined in IEEE 1528 or vigorously validated by SAR system manufacturers, is unavailable and method A is not suitable. It should be ensured that SAR discrepancies due to probe conversion factor and tissue dielectric parameter differences between the dipole and probe calibration frequencies are also acceptable; for example, less than 10 – 15%. The dipole should have a return loss of -15 dB or better at the measurement frequency for both method A and B.

[13] The alternative system verification methods A and B described in this document should be used. Contact the FCC for possible options when these alternative methods are not suitable.

[14] Manufacturer calibrated SAR target values at offset frequencies are required. IEEE 1528 requires a return loss of -20 dB or better for reference dipoles; however, when reference dipoles are unavailable and alternative procedures must be used, a return loss of -15 dB or better is acceptable for the interim.

When method B is required, tissue dielectric parameters measured at the dipole frequency should be within ±10% of those required at that frequency.[15] This allows an operating range of approximately ±120 – 250 MHz or more to cover most situations above 300 MHz and ±100 MHz or more below 300 MHz. The probe conversion factors at the dipole and probe calibration (device measurement) frequencies should be analyzed to ensure SAR discrepancies are expected to be < 5%.[16] These should generally keep the new SAR target within 10 – 15% of the original target calibrated according to probe calibration and tissue parameters specified for the dipole frequency.[17] The new dipole target should be established with at least 5 or more measurements, each reconfigured from scratch, with a coefficient of variation < 2%; that is, (standard deviation)/mean < 0.02.[18] When the same dipole is used for system verification required by other test devices and the same tissue recipe and probe calibration are used, all previous data should be applied to compute the coefficient of variation; until the probe is recalibrated or a new tissue recipe is required. In all subsequent cases, the coefficient of variation should be less than 3% and the mean should be within 15% of the original SAR target calibrated according to probe calibration and tissue parameters required at the dipole frequency. System verifications using alternative method B must include all results and analyses in the test report to justify such use, including dipole return loss plots, SAR discrepancy analyses of probe conversion factors, tissue dielectric parameter measurements and coefficient of variation calculations etc.

Measurement Uncertainty

The measurement uncertainty procedures described in Supplement C 01-01 and IEEE Standard 1528 should be followed, whichever are more conservative. Although measurement uncertainty procedures are not available for assessing the alternative system verification methods A and B described in this application note, when quantitative estimates are not feasible a qualitative estimate of the measurement uncertainty due to deviations from the required measurement protocol should be included in the SAR report. The expanded SAR measurement uncertainty should be ≤ 30%, with a confidence interval of k=2, for all measurements.

---

[15] The SAR probe is calibrated according to the frequency and tissue parameters required by the test device.
[16] SAR changes can be analyzed according to equations used to convert the measured field values to SAR. The information is usually included in SAR system reference manuals. Also see footnote 17.
[17] This also minimizes problems that may not be easily detected when reliable SAR target are unavailable. Up to 10%SAR variations due to probe conversion factor differences may be accepted when SAR variations due to tissue dielectric parameter differences are low and the overall difference between new and original SAR targets is within 15%.
[18] This can be easily computed with an Excel Spreadsheet.